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## CHARACTERISTICS OF MULTI-YEAR PRESSURE RIDGES

### Abstract

Multi-year pressure ridges and thick hummock floes are the most severe ice formations that offshore structures will probably have to resist in the Beaufort and Chukchi Seas. Multi-year hummock fields 30 m thick have been measured near Prudhoe Bay, Alaska [4]. This paper presents information on 11 multi-year pressure ridges. The ridges were found to be voidless, and contained ice with a mean brine-free density of about  $0.84 \text{ Mg/m}^3$ . The apparent unconfined compressive strength was about 7 to 8 MPa at  $-10^\circ\text{C}$ . The strength increased with depth below sea level, and, as expected, varied inversely with ice porosity. The sail-height-to-keel-depth ratios of these ridges are compared with observations made in the Beaufort and Chukchi Seas to show that the multi-year ridges in these areas have a relatively constant sail-height-to-keel-depth ratio of about 1 to 3.3.

### 1. INTRODUCTION

Sea ice fails when the internal stresses in the pack exceed the strength of the interacting ice. One or more of the interacting ice sheets fails in bending, flexure or crushing, and frequently broken ice accumulates into an isolated ridge or rubble pile. If ice stresses remain high, deformation may continue until a large area of the ice cover is destroyed and the broken ice blocks are pushed into a haphazard accumulation of mounds and ridges called a hummock field.

Ridges formed during the course of a winter are called first-year ridges. The highest free-floating first-year ridge ever measured was 12.8 m high, and was found in 1971 in the Beaufort Sea [7]. The deepest ridge keel ever measured was just 50 m, and was found in the Lincoln Sea in 1975 by the submarine USS Bluefish. From analyses of thousands of kilometers of submarine sonar profiles of the ice bottom and laser profiles of the ice surface relief, it is clear that both the ridge sail height and keel depth given above are extremely rare. Indeed, ridge keels deeper than 30 m are also very infrequent. Studies of first-year ridge geometry have indicated that the sail-height-to-keel-depth ratio is about 1 to 5 [7].

During the melt season, the angular ice blocks of the ridge sail and keel gradually become rounded by ablation processes, the inter-block

voids fill with fresh water from the melting of surface snow and ice, and the overall relief of the ridge becomes smoothed. The downward migration of surface melt dilutes the unfrozen seawater between the ice blocks in the keel. In time this water freezes in the interlock voids of the ridge. This bonds the blocks together and increases the structural integrity of the ridge. Ridges which survive one summer's melt season are properly called second-year ridges, and those which survive two or more melt seasons are referred to as multi-year ridges. The latter term, however, is often used to explain both features because of the general difficulty of distinguishing one from the other.

Multi-year ridges can be very large and structurally sound [8]. They not only prevent the passage of even the largest icebreakers but also pose a difficult problem to engineers designing offshore structures capable of resisting the forces which may develop when these strong ice formations are pushed against the structure.

To date, there is information available in the open literature on about seven field studies in which about 55 "multi-year" pressure ridge cross sections have been presented [e.g. 3, 5, 6, 7, 8, 9, 12]. Information [5, 6, 7, 8, 9, 12] indicates that a fairly constant relationship exists between the sail heights and keel depths of second-year and multi-year pressure ridges in the Beaufort and Chukchi Seas of about 1 to 3.3. In disagreement with this finding is the ratio of 1 to 5.6 found in a study of multi-year ridges in MacLean Strait west of Ellef Ringnes Island in the Canadian Arctic [3].

This paper presents information on the geometry and structure of 11 second-year pressure ridges (hereafter referred to as multi-year ridges) studied in 1982 in the Beaufort Sea between Reindeer Island and Harrison Bay, Alaska. Information is given on the sail-height-to-keel-depth ratios of isolated multi-year pressure ridges and multi-year ridges and hummocks found in rubble field floes as well as information on the relative thickness of the multi-year floe ice, and the properties of the ice.

## 2. RIDGE INVESTIGATIONS

The surface relief of the ice was determined by elevation survey. The draft of a ridge keel was determined by direct drill hole measurement or by horizontal sonar ranging. These procedures are the same as those used and described in many previous studies [5, 6, 8, 9]. However, in this study the sonar transducer that was used produced a 7-1/2° beam angle at the 3-dB points as compared to about a 3° angle in the studies cited earlier. This transducer was selected because it required a 10-cm-diameter, easier-to-drill access hole versus the 22-cm-diameter hole required for the 3° beam transducer. The disadvantage of using a transducer with a 7-1/2° beam is that it senses a larger target area and thus tends to see relief outside of the keel surface of interest, directly in front of the transducer. In short, the use of a transducer with a 7-1/2° beam will tend to produce ranging data which make the keel appear closer to the trans-

**ducer and** make the keel appear deeper than **it** is. The apparent keel geometry constructed from the sonar measurements would thus tend to be slightly larger than it **really** is, or on the conservative side for design purposes.

Drill holes for direct measurements of ridge ice thickness were made using 50-mm-diameter, 1-m-long stainless steel auger flights which snapped **together** to form a continuous flight of unlimited length. The auger was turned using a hand-held 15-mm heavy duty electric drill. **Augering** in this way allowed the driller to sense whether there were cavities or "soft ice" **areas**.

Ice cores about 76 mm in diameter were obtained at two ridges to determine the temperature, weight and salinity of the ice with depth. From **these** measurements the density, porosity and brine **volume** of the ice were determined. The apparent unconfined compressive strength of the ridge ice was also determined by testing the ice cores in a **special** axial double-point loading device [11].

### 3. RESULTS

Cross **sections of** six of the ridges studied are given in Fig. 1-6. These cross sections are presented to show the extreme variations which exist in the ice relief under the ridge sails. Under one ridge there was no unique ice protrusion typifying a ridge **keel** (Fig. 4), while **in** other cases the keel was displaced a substantial distance to one side (Fig. 6), presumably as a **result** of an event in which ice rafting occurred followed by ridge building at the ends of the **overlapped** ice sheet thrust lobes. The ice relief under a multi-year floe formed in a rubble field is interesting in that under one of the highest ridges the ice had the **least** draft (see ridge A, Fig. 1).

If the deepest ice in the area below a ridge is compared with the highest ridge sail elevation measured, then the results **listed** in

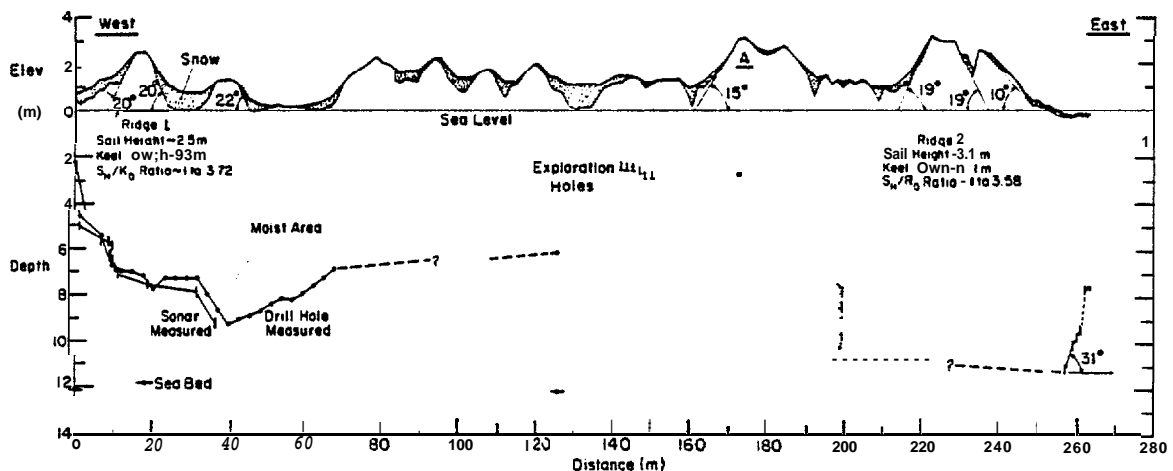


Fig. 1. Cross section of multi-year rubble **field** floe with numerous hummocks **and** ridges. Note shallow ice depth below ridge A.

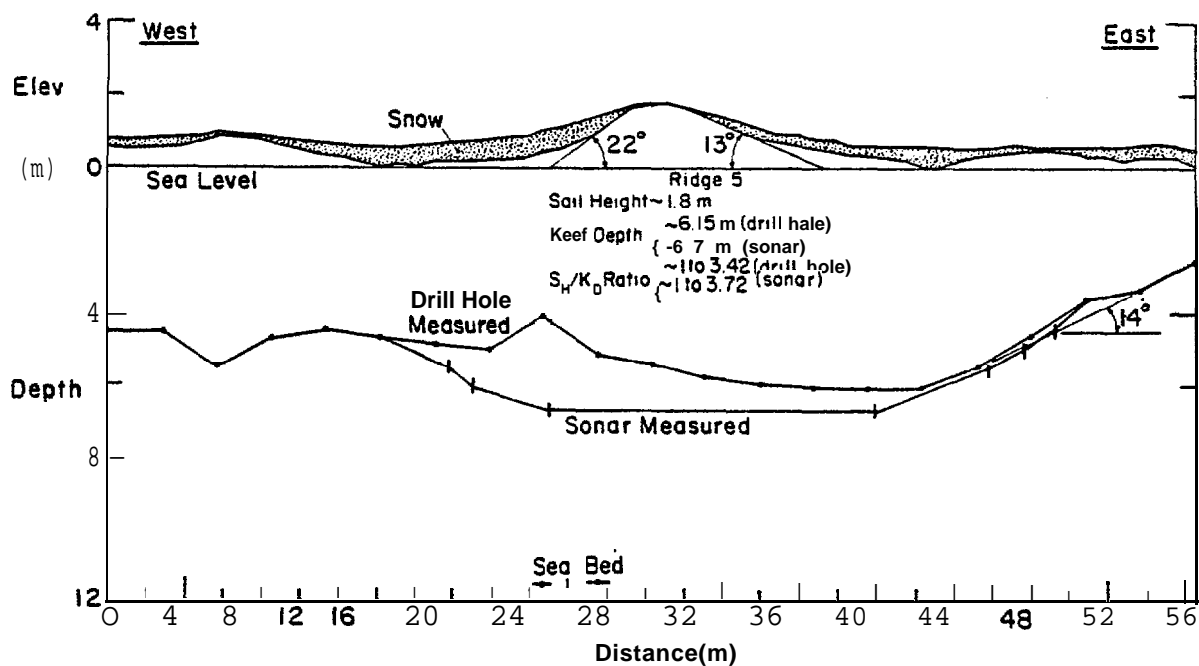


Fig. 2. Cross section of ridge 5. Note that under this ridge sonar ranging indicated deeper ice than that measured by drilling.

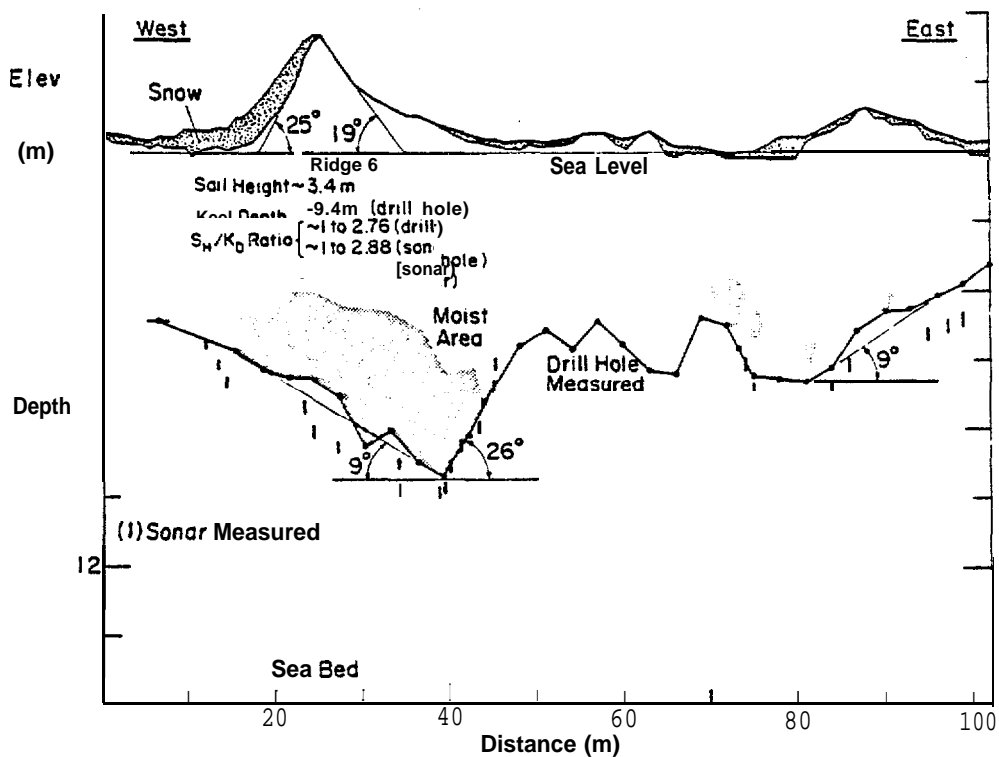


Fig. 3. Cross section of multi-year floe. Note moist ice areas encountered during drilling.

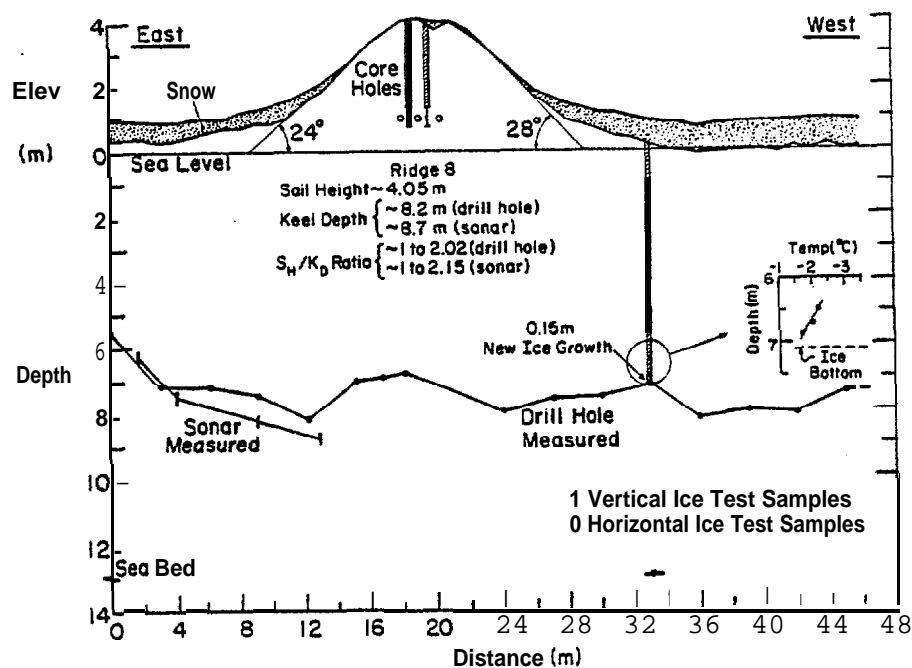


Fig. 4. Cross section of ridge 8.

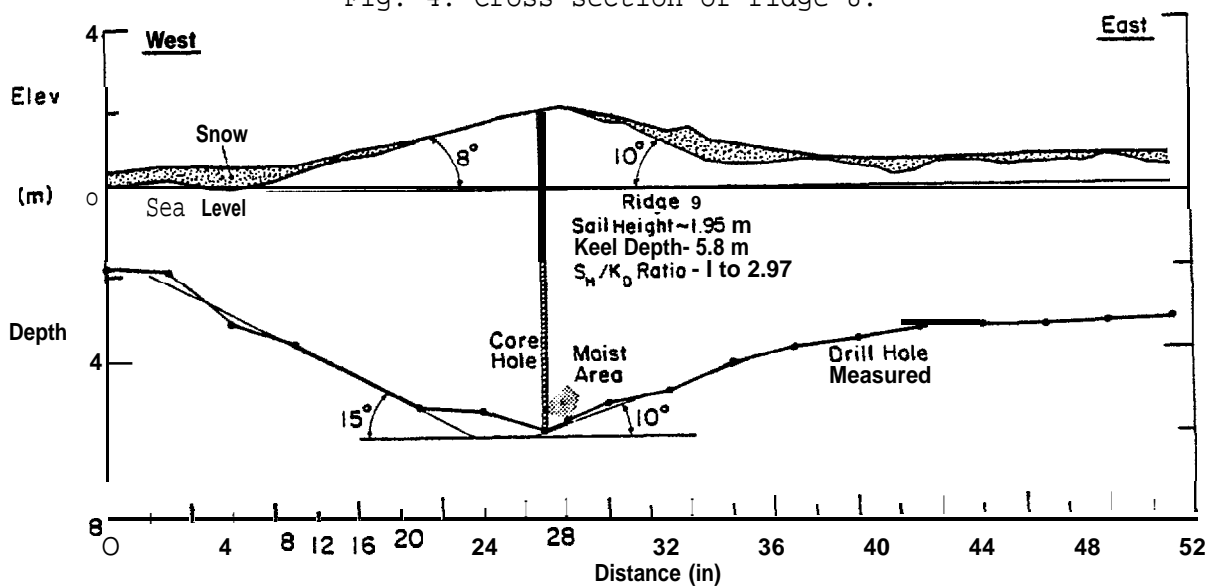


Fig. 5. Cross section of ridge 9.

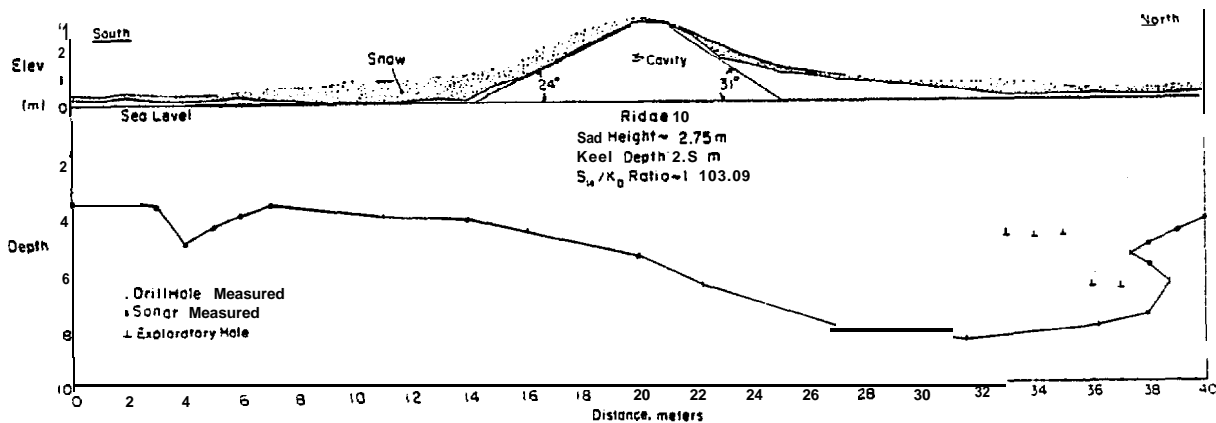


Fig. 6. Cross section of ridge 10.

Table 1. Ridge **sail** heights and keel depths.

Ridge no.	Sail height (m)	Keel depth* (m)	$S_H/K_D$
1	2.5	9.3	1/3.72
2	<b>3.1</b>	<b>11.1</b>	1/3.58
3	2.4	9.6	1/4.00
4	3.15	10.8	1/3.48
5	<b>1.8</b>	6.7	1/3.72
6	3.4	9.8	1/2.88
7	4.05	12*2	<b>1/3.01</b>
8	4.05	8*7	1/2.15
9	1.95	5.8	1/2.97
10	2.75	8.5	1/3.09
11	3.0	8.5	1/2.83
Mean = 1/3.22			
S.D. = 0.53			

\* Deepest ice draft measured by drilling or sonar.

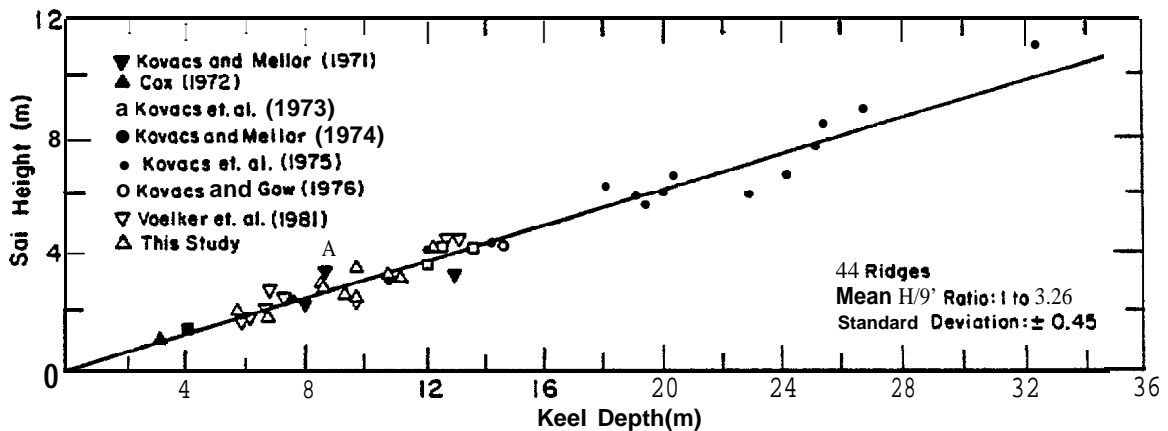


Fig. 7. Relationship between multi-year pressure ridge sail height and keel depth.

Table 1 are obtained. The mean **sail** height ( $S_H$ ) to keel depth ( $K_D$ ) ratio for the 11 ridges is 1 to 3.22. This ratio is in good agreement with the mean ratio of 1 to 3.26 obtained for the combined data set of 44 multi-year pressure ridges **studied** in the Beaufort and **Chukchi** Seas, as shown plotted in Fig. 7.

Twenty-five ridge sail **slope** angles were calculated from the elevation **survey** results. The mean slope was found to be 20.9° with a standard deviation of 7.0°.

In this study over 1100 m of vertical **hole** was augered into various multi-year ice formations. As with previous studies [5, 6, 8, 9], no cavities were encountered. However, pockets of "soft,\*<sup>g</sup> moist ice" were encountered at depth in several of the ridges (Fig. 1 and 3). These pockets represent sites of incomplete freezeback or keel solidification, and may represent zones of critical weakness in the ice mass.

An ice core through ridge 9 was obtained at the position shown in Fig. 5. The salinity, porosity and density of the ice were calculated based upon the measured ice core temperature, and the weight, length and diameter of each ice core sample were also measured. The salinity, temperature, porosity and brine-free ice density versus depth are plotted in Fig. 3. The salinity increased from near zero at the top of the ridge to about 1‰ at sea level. It then decreased to about 0.3‰ for a depth of about 1 m below sea level, and then rapidly increased to an average value of about 1.8‰ down to about 1/4 m above the ridge keel bottom.

The last 0.15 m of the ice core was found to consist of new sea ice growth in which the c-axes of the ice crystals were aligned in a preferred direction in the horizontal plane. This alignment is a common phenomenon found at the bottom of first-year sea ice [10, 13]. In this layer the salinity of the ice increased to about 8‰. Ice porosity is shown to trend from about 11% at sea level to about 6.5% 1/2 m above the ice bottom. Above sea level the ice porosity was about 8%. Ice porosity was calculated using an exacting procedure recently devised for sea ice [2].

The density of the brine-free ice ( $\rho_i$ ) is shown to increase gradually with depth from about 0.825 Mg/m<sup>3</sup> at sea level to about 0.875 1/2 m from the bottom. The mean bulk brine free density of the ridge ice was 0.843 Mg/m<sup>3</sup> with a standard deviation of 0.020 Mg/m<sup>3</sup>.

Shown on the right side of Fig. 8 is the apparent unconfined compressive strength ( $u_{ca}$ ) and the porosity (N) of the ridge ice versus depth. The indirect double point  $\sigma_{ca}$  tests were made at an effective strain rate of  $10^{-3}$  at -10°C. The porosity is that calculated for brine-free ice at this temperature. Since there is no acceptable temperature correction factor for the unconfined compressive strength of ice above -5°C these strengths were not corrected to the in-situ temperature of the ridge. As expected, N and  $\sigma_{ca}$  have similar but opposite trends. That is, as N decreases  $\sigma_{ca}$  increases and vice versa. The mean of the  $\sigma_{ca}$  values was 7.90 MPa with a standard deviation of 1.99 MPa.

At ridge 8 vertical and horizontal ice cores were collected at the same relative elevation in the ridge sail (Fig. 4). The horizontal cores were obtained by drilling 2 m into the face of the ridge where it had split apart. Ice strength tests were made at -17°C to determine if there was a significant difference in the apparent unconfined compressive strength of the ridge ice in the horizontal versus the vertical plane. Fifty-six vertical and 61 horizontal tests were made. The vertical cores had a mean  $\sigma_{ca}$  of 7.50 MPa (standard deviation 1.18 MPa) and a mean  $\rho_i$  of 0.831 Mg/m<sup>3</sup>. The horizontal cores had a mean  $\sigma_{ca}$  of 7.99 MPa (standard deviation 1.67 MPa) and a mean  $\rho_i$  of 0.822. While the vertical cores had a higher mean  $\sigma_{ca}$ , statistically there is no significant difference since the vertical and horizontal mean  $\sigma_{ca}$  values fall within the standard deviation of the opposite test. When all the data are combined into one test population, the mean  $u_{ca}$  and  $\rho_i$  become 7.76 MPa and 0.827 Mg/m<sup>3</sup> respectively.

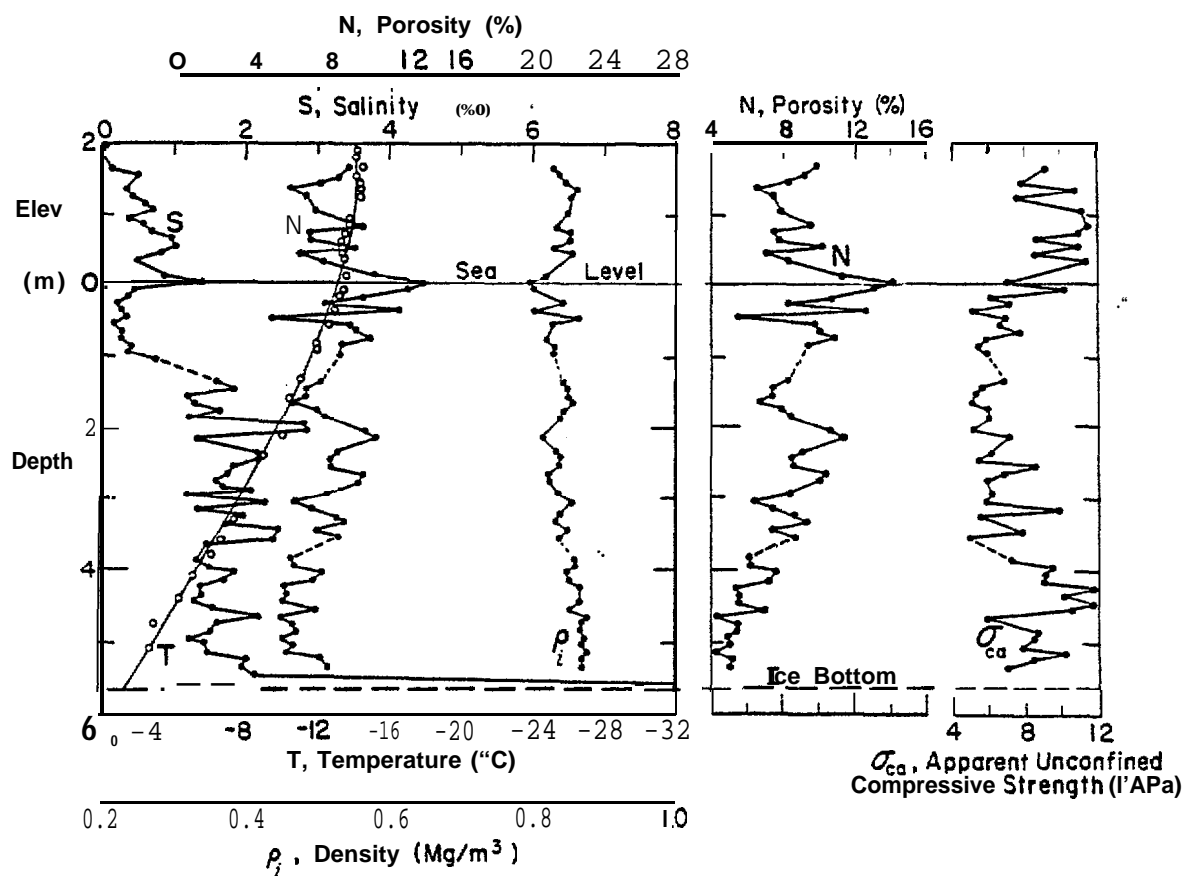


Fig. 8. Salinity, porosity, temperature and brine-free density of the ice versus depth in ridge 9, and the apparent unconfined compressive strength and porosity of the ice at -10°C.

#### 4. DISCUSSION AND CONCLUSIONS

Additional information **was** presented on the geometry of multi-year pressure ridges. While the cross sections presented show a large variation in the shape of the ridge keel it was found that the sail-height-to-keel-depth ratio for the multi-year ridges studied was relatively constant at 1 to 3.22. On the basis of 44 ridges studied in the Beaufort and Chukchi Seas to date, the sail-height-to-keel-depth ratio is 1 to 3.26 with a standard deviation of ( ).45.

New sea ice growth was observed on the bottom of the two ridges from which ice **cores were** obtained in this study. This indicates that sufficient time existed during the 1981-82 winter cooling cycle to **lower** the internal temperature of the ridges and **allow** sufficient heat removal from the ice bottom so that new ice growth occurred. In ridges over 8 m deep or where a thick layer of snow existed, sufficient heat flow may not have occurred to allow complete **freezeback** and solidification of the ridge keel. The penetration of **moist** ice zones in a number of the ridges suggests that this may be so for second-year ridges. Other studies [5, 6, 8], however, suggest that for older multi-year ridges the internal structure is composed of essentially solid ice.



The mean apparent unconfined compressive strength for ice from the sail of one ridge tested at  $-17^{\circ}$  C was 7.76 MPa. This value is in general agreement with the  $\sigma_c$  values obtained from right cylinder **uniaxial** unconfined compression tests at a strain rate of  $10^{-3}$  currently being made at **CRREL** using multi-year sea ice of similar density. In these tests the right cylinders are **0.102** m in diameter and **0.254** m long (**G.F.N. Cox**, personal communication).

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